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ANALYSIS OF LARGE URBAN FIRES*

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ABSTRACT

Fires in urban areas caused by a nuclear burst are analyzed as a first step towards determining their smoke-generation characteristics, which may have grave implications for global-scale climatic consequences. A chain of events and their component processes which would follow a nuclear attack are described. A numerical code is currently being developed to calculate ultimately the smoke production rate for a given attack scenario. Available models for most of the processes are incorporated into the code. Sample calculations of urban fire-development history performed on the code for an idealized uniform city are presented. Preliminary results indicate the importance of the wind, thermal radiation transmission, fuel distributions, and ignition thresholds on the urban fire spread characteristics. Future plans are to improve the existing models and develop new ones to characterize smoke production from large urban fires.

INTRODUCTION

The impetus for the present work stems directly from the "nuclear winter" issue. "Nuclear winter" refers to the wide-spread, long-term cooling predicted to occur due to the injection of teragrams of smoke particles into the stratosphere as a result of fires caused by a large-scale nuclear war. Given the wide variations that exist among many possible scenarios derived under various assumptions [1-3], a more detailed analysis is needed of smoke-production processes in the aftermath of a nuclear war to determine the plausibility of "nuclear winter". There appears, however, to be no comprehensive study treating in detail the very complex processes governing these phenomena.

Numerous factors are involved in characterizing the climatic effects. These factors have wide uncertainty bands owing to the paucity of reliable data and the lack of sufficient understanding of the processes. Among the more obvious processes are the large-scale urban fires and smoke-production phenomena, the plume and smoke transport dynamics, and the global-scale smoke spread phenomena. Here we investigate one of these: the generation (rate and amount) of smoke particles from large fires after a nuclear burst over an urban area. Many factors need to be considered and correct models of their physics should be introduced to characterize the smoke-generation processes, especially for large urban fires produced under nuclear conditions. However, due to the dearth of available experimental or theoretical studies of large fires on an urban scale - to say nothing of the smoke characteristics - large gaps exist in our understanding of the interactions between the burning fires and the smoke generation processes. As a first step in addressing this complicated physico-chemical problem, we are investigating theoretically the time-dependent fire spread in an urban area following a nuclear attack.

We are pursuing the following three-step approach to reduce the uncertainties:

(1) develop numerical codes incorporating currently available physical models for the various factors involved in urban fires and smoke analysis;

(2) perform sensitivity analysis to identify dominant parameters; and

(3) propose new models and modify current models which require improvement.

ANALYSIS

Urban Fires/Smoke Generation Processes

To determine the amount of smoke generated in an urban area following a nuclear attack, we need information on the state of fires, such as the area burn history, the fire intensity, and the fuel consumption characteristics. This requires information such as the yield and burst point of the nuclear weapon, the weather conditions, urban complex distribution patterns, etc. These various factors and their interrelationships are conceptualized and shown in Fig. 1. The input conditions (left and the right columns) are necessary for calculating the fire and smoke generation history (center column). We emphasize that all of the factors mentioned in the

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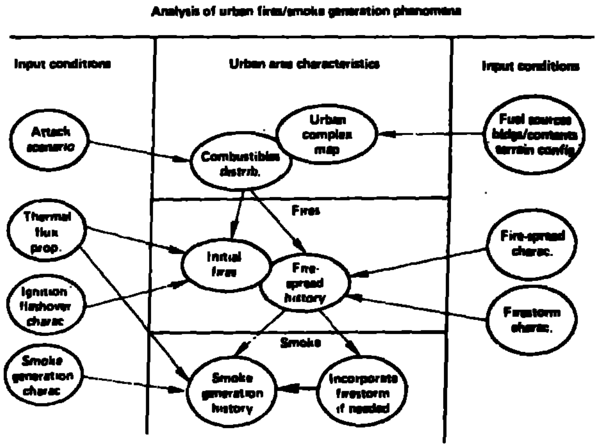

Figure 1. Conceptual overview of the Urban Fire and Smoke Generation problem.

figure——whether input conditions or the analysis functions——require modeling, either from empirical results or theoretical considerations. In assembling these models and approaching the analysis in a coherent manner, the following chain of events was developed for characterizing urban fires and smoke history (Fig. 2). These are: attack scenario, thermal flux propagation, initial fires, blast effects, fire development, fuel consumption, and smoke production. In what follows, we describe in greater detail the various physical parameters and factors involved in each stage.

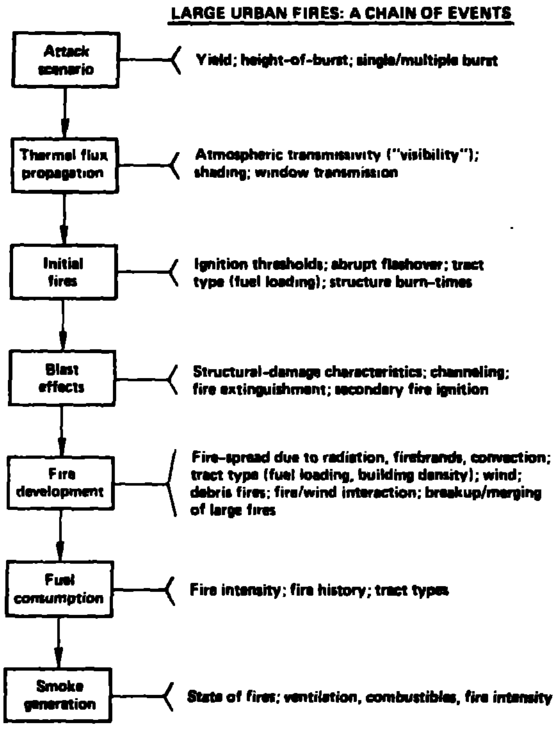

Figure 2. Chain of events for characterizing urban fires and smoke generation.

Relevant Physical Parameters

Attack Scenario. Three factors comprise what we call the attack scenario: the yield of the weapon, the height-of-burst (HOB), the location of ground zero (GZ), and altitude of the urban area. (We limit consideration to single-burst cases.) The attack scenario is generally assumed specified.

Thermal Flux Propagation

Two factors are considered here. They are the thermal radiation transmission characteristics through a given atmosphere, and the shading of some or all of the thermal radiation by intervening objects. The atmospheric conditions are important because they affect the propagation behavior of the thermal radiation of the fireball and the subsequent fire development history. The scattering characteristic of the atmosphere is simply expressed in terms of the visibility [6]. The visibility depends on whether it is a clear, cloudless, or foggy day. Since we do not know the atmospheric conditions at the time of attack, we vary the visibility parametrically to see its effect on the fire history, especially in the initial stages of fire development.

Another factor in determining how much of the fireball flux arrives at a building is the shading caused by whatever comes between the fireball and a target structure, such as a fence, a hill, or another structure. Currently we account for partial obscuration of the fireball by the nearest neighbor building and, for the first two floors, by awnings and trees.

Initial Fires

We include five factors in this category: the ignition characteristics, the window transmissivity, abrupt flashover, the fuel-loading distributions, and the structure burn-times. Once the thermal radiation fluxes arrive at the structures, ignition can start on the walls and inside the rooms. It has been observed [7], and is expected from the energy required to ignite thick fuels, that wall ignitions are relatively minor, and that the bulk of the building fires are caused by the radiation that penetrates into the rooms through the windows. Therefore, we assume in our model that initial fires caused by the fireball are due to ignition of the window coverings and the room contents only. (This is not a severe constraint because any building whose walls could be ignited would most likely have more susceptible fuels as well.) Thus we need information on how much of the fluence was transmitted through the window and impinged on the major ignitable materials inside the room. What catches fire obviously depends on what ignitable materials are directly exposed to the radiation flux. Because the distribution patterns of these ignitable materials in various buildings in an urban area are diverse, a probabilistic treatment using the results of field surveys of actual cities is necessary [8]. The ignition thresholds of various materials have been measured and estimated. Typical values range from 10-60 cal/cm^2 for a 5 MT weapon [8]. The rate of energy deposition is also important, and is incorporated into the published threshold values. It is necessary to scale the 5 MT values for other yields since lower yield weapons have shorter thermal pulses. In the present model we use four different ignition threshold values These values can be changed to characterize the susceptibility of the various window coverings and room contents.

The third factor is the abrupt flashover phenomenon, which is believed to have been observed in one nuclear test, the "ENCORE" Event in 1952 [9]. It is hypothesized that the very rapid deposition of energy by the thermal pulse of the explosion caused the exposed room to behave in a qualitatively different fashion than a room heated by fire to conventional flashover. Whereas a conventional flashover occurs on the order of 30 minutes after fire start, "abrupt flashover" can occur on the order of 30 seconds. Little understanding exists as yet on the subject. Although possibly important, we have not yet included this parameter in our considerations of fire development due to the lack of quantitative models. The fourth factor in this category is the fuel loading pattern. This depends on the particular urban area or at least on the region in the country. Clearly the distribution patterns of combustible materials in an urban area will greatly affect the fire phenomena, not only of the initial fires but also the subsequent fire development and the smoke generation history. Comprehensive surveys of various urban areas will yield necessary input information for our study. In the mean time, various fuel loadings are considered and their effects on the fire phenomena are investigated in the present analysis.

The fifth factor used in our modeling is the building burntime. Folded into this parameter are various other factors such as the number of stories of the building, the specific fuel loading, rate of fire spread across a floor and the average times for fire to spread up one floor and down one floor. The building burntime is a convenient parameter used by Takata et al. [10]. It increases for taller buildings or those with a higher fuel loading. The burntime is varied in our sensitivity study when we vary the specific fuel loading to determine its influence on the development of fires.

Blast Effects

Three factors are included in this category: structural damage criteria, fire extinguishment due to blast waves, and fire starts due to blast damage (often called "secondary fires"). For example, it is generally expected that an overpressure of 2 psi (14 kPa) will cause light to moderate damage to well-built wooden buildings, but the building will remain standing. An overpressure of 3.5 psi (24 kPa) or greater will inflict severe structural damage on the buildings, reducing them to rubblized debris. The specific value of the damage thresholds depends upon the type of structure being considered, and the angle of the blast wave impinging on the structure. No definitive analysis exists on the damage criteria. Moreover, the blast wave experienced by a structure is significantly affected by the surrounding structures and topography. Since this is not our primary area of concern we treat these damage thresholds (moderate and severe) as given values in our analysis. The second parameter, the extinguishment of incipient fires by the blast wave, has been the subject of interest in recent years [11]. No conclusive results are available; thus we use a simple algorithm based on overpressures [5]. The third factor, the secondary ignitions, are potentially important, but still very uncertain. Here we use an estimate based on analysis of fires caused during earthquakes, tornadoes, and World War II [12].

Fire Development

In this category we include six factors: the fire-spread characteristics, the ambient wind effects, the breakup and/or merging of fires, firestorms, the fire-wind interaction, and the smoldering debris fires. These factors constitute an important element in our ultimate objective of calculating the amount of smoke particles generated from urban fires. Despite their importance, very little is known or understood about some of these phenomena. One reason is that each factor is a combination of various complex physico-chemical processes. Therefore, in our first step towards characterizing urban fire history, we treat only some of these factors, i.e., the fire-spread characteristics and the ambient wind effects. We thus emphasize that the present paper is a preliminary analysis.

Many factors determine the fire-spread characteristics of large-scale fires in an urban area, e.g., the spread mechanisms (firebrands, thermal radiation, convection), the combustible distribution patterns (fuel loading characteristics), the building density, and the building burntimes. Some modelling of these factors has been performed in the past. We are limited, however, by the small amount of relevant data on laboratory or full-scale. We are also limited by the wide variability of the many factors which come into play in actual fires. The general approach has been to model a simplified or worst case. For example, the thermal radiation fluxes impinging on unburned buildings can be expressed in a rather straightforward manner in terms of the viewing factor, the fire temperatures and emissivity. Or consider the ambient wind effects on the fire development. It has been observed on numerous occasions that the wind greatly enhances the burning processes and that the flight of the firebrands in the windward direction is the predominant cause of fire spread, both in urban and forest fires. Thus the generation and transport of the firebrands of various sizes is an important component in characterizing the fire spread (conflagration) phenomena. Until a separate analysis is completed of the fire-induced wind effects, we take the wind in our current model as prescribed. The wind transports the firebrands in the downwind direction causing fires to spread from building to building and from tract (a collection of buildings) to tract. Because the fire-spread process is highly stochastic in nature owing to the various uncertainties involved, we have performed sensitivity studies to identify the dominant parameters.

Fuel Consumption

The amount of the fuel consumed is an essential component in determining the amount of smoke generated. The fuel consumption is dependent upon the tract types (i.e., the fuel loading and the building density, etc.), the intensities of the fires, and the extent of fire spread. It is typically estimated that half of the fuel in an ignited building is consumed in active burning, with the balance either extinguished or smoldering for a very long time. Therefore we neglect this latter half in the present context of urban fires lasting hours or at most just over a day.

Smoke Generation

Although many results are available for the smoke generation tests performed in laboratories for various materials [13-14], the laboratory-scale results may not serve as a sufficiently reliable guide to quantify the amount of smoke produced in very large scale fires. The dominant reason for such tenuous connection between the small laboratory scale tests and the large urban fires is that the complex interactions that take place between the aerodynamics surrounding the burning buildings and the burning materials have not been tested in the laboratory; moreover, laboratory tests using scaled-down versions of the burning buildings will be extremely difficult to perform so as to simulate correctly the turbulent length scales, to mention only one aspect of the total fire and smoke production processes involved in full scale urban situations. It nevertheless appears to be true that locally the smoke-production phenomena are dependent on three major factors: the ventilation effects, the nature of the materials involved, and the fire intensity. We concentrate in this paper on the fire aspects and defer the smoke production analysis to a future effort.

Current Models

In this section we describe in more detail the models used to characterize the large urban fire phenomena, starting from the attack scenario to the fire spread processes.

From the assumed yield and height-of-burst, we calculate the free-field overpressure as a function of distance from ground zero [4] (Fig. 3). The overpressure at the center of each tract is used to determine the structural state of the buildings—debris, moderately-damaged, or undamaged. The overpressure also determines the fraction of the fires started by the fireball which is extinguished by the blast. The algorithm used for blast extinguishment is very simple, based on a small number of shock tunnel experiments (see Ref. 9 for the original references). Some additional fires, i.e., secondary ignitions, are expected as a result of blast effects on urban areas, such as gasline ruptures and downed electrical power lines. The number of such fires per building is estimated based on the floor area, using empirical data from various disasters [12]. The calculation of the ignition probability by the fireball proceeds as follows. At each increment of distance from GZ, the free-field thermal radiation fluence is calculated using the slant range and the atmospheric visibility (a measure of attenuation by scattering). For our baseline case, Gibbons [6] gives the attenuation factor as a function of the slant range, fireball radius, and visibility. The free-field fluence is further reduced as the inverse square of the slant range.

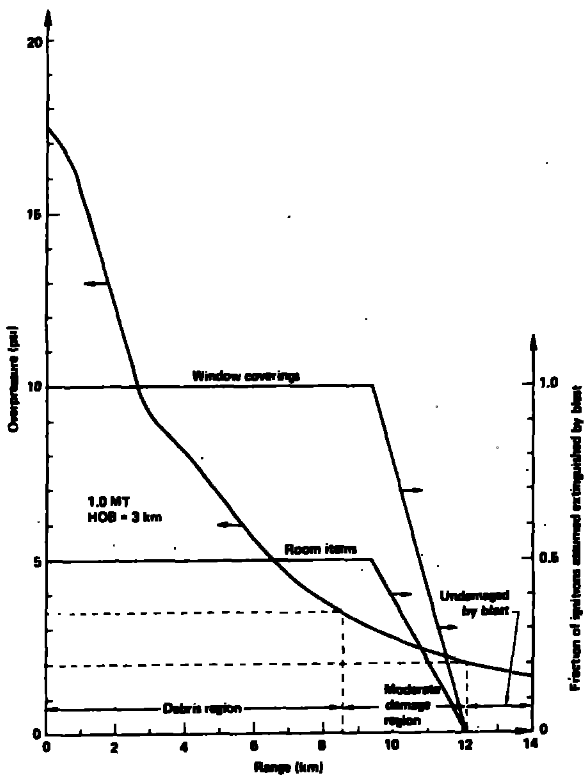

Figure 3. Free-field blast overpressure vs. range from GZ, and (assumed) blast effects on structures and fires.

Next we need to determine how much of the free-field fluence actually reaches something ignitable. Since only interior fuels are considered, the problem becomes one of calculating how much energy impinges upon window coverings and upon fuels in the room. For each tract type, we account for shielding of the fireball by the nearest neighboring building and for shielding of the first two floors by trees and awnings. The distribution of building separation in selected American cities has been found from surveys to be quite similar [8]. In addition, the number and sizes of the windows have been obtained from surveys of the same cities. The irradiance is calculated at each window and at various horizontal areas within each room. The probability of finding ignitable room items in such areas, as well as the frequency of occurrence of window coverings and room contents in various categories of ignitability ("critical ignition energies", see Fig. 4) have also been obtained from surveys.

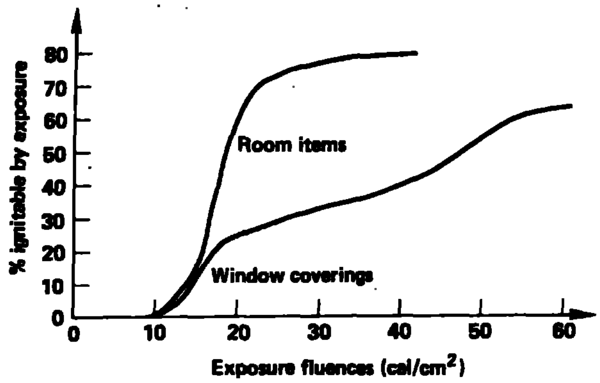

Figure 4. Probability of ignition of a major room item or window covering vs. exposure fluence from the fireball of a 1 MT explosion. This incorporates the results of field surveys of combustibles in U.S. cities (Ref. 8).

The critical energies required for ignition increase with the thermal radiation pulselength, which is yield-dependent; hence the critical ignition energies scale roughly as the yield to the 1/6 power.

The above information is then used to calculate the probability of ignition of the window coverings or at least one major room item. Based upon analyses involving room surveys, 40% of the ignited window coverings are considered capable of causing sustained room fires. After calculating these intermediate probabilities, we finally calculate the probability of at least one sustained room ignition in a building due to the fireball. The probability of blast-caused secondary ignitions is then factored in. The result is the probability of sustained building ignition as a function of distance from GZ for each tract type. Results for our baseline case, which incorporates the blast extinguishment effects indicated in Fig. 3, are shown in Fig. 5. The solid curve represents the sustained ignitions due to both thermal radiation and the blast, while the dotted line indicates just the blast-caused ignitions for the region where the overpressure exceeds 2 psi.

Once the immediate effects of the explosion are over, it is necessary to calculate the spread of fire from burning to non-burning buildings. To this end we must specify the average length of time a given building type will spend in active (flaming) burning, and the probability, at each time step, for a burning building to spread fire by short-range mechanisms (thermal radiation with or without sparks) and by firebrands. For this purpose we applied simple models and empirical factors. Figure 6 shows "time-of-spread probability" curves [15]. These curves should be normalized by an estimate of building burn duration. Estimates are calculated by assuming ignition of a single room by exterior sources. A number of floors and specific fuel loading, i.e., mass of fuel per unit area per floor, are specified. In addition, estimates

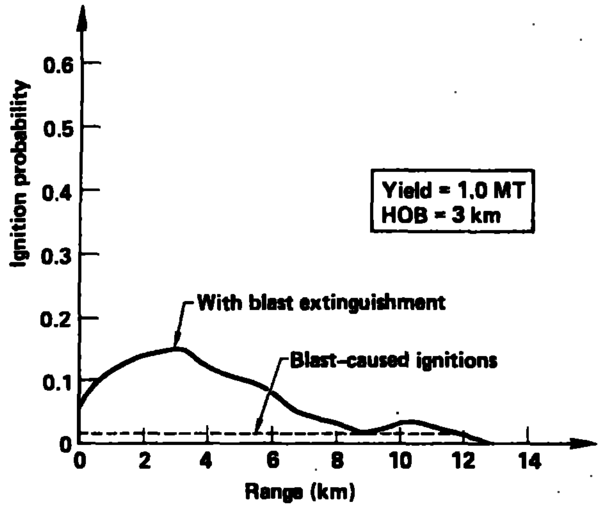

Figure 5. Ignition probability vs. range from GZ for a residential tract, assuming significant blast extinguishment of incipient fires. Blast extinguishment and secondary ignitions cease for ranges greater than 12.1 km.

were provided for the rate of fire spread across a floor and fuel consumption rate, and the average time required for fire to move up one floor or down one floor. (It is assumed that only half the fuel is consumed while the building is burning down.) We can calculate the time for the building to burn down if we assume which floor was initially ignited. If we assume, as here, that any floor is equally likely to be initially ignited, then we can determine the average burn duration of each building type. For our baseline case, we find a burn duration of 71 minutes, which is somewhat excessive because of the neglect of multiple ignitions. For this reason and because we use 15 minute timesteps, we "force" the fuel to be consumed in 60 minutes (Fig. 7). It is obvious that

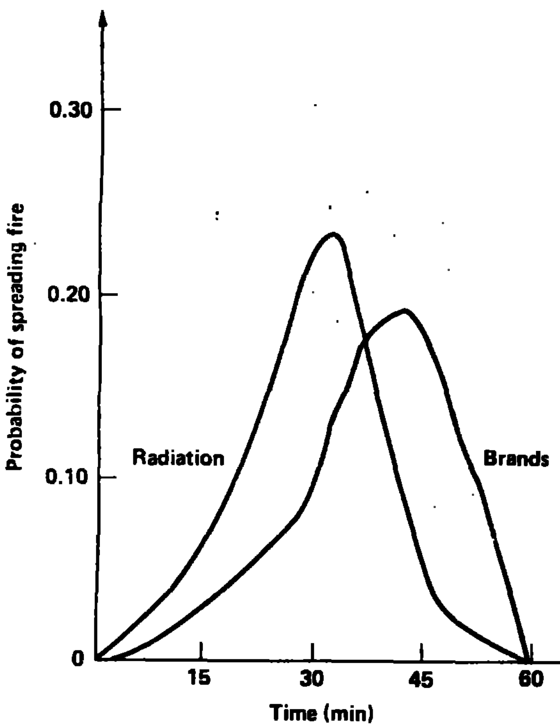

Figure 6. Probability of a burning building spreading fire during its time of active burning. (Ref. 10)

there are many uncertainties regarding how long an average building burns and when it spreads fire. Nevertheless the results appear qualitatively reasonable based upon limited experimental work and accidental building fires.

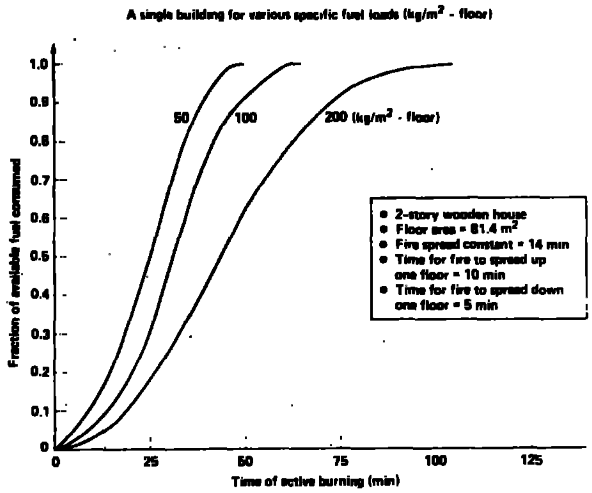

Figure 7. Fuel consumption vs. time for an isolated building with a single ignition point, for various specific fuel loadings.

The spread of fire over short distances is primarily due to thermal radiation with and without the presence of sparks ("piloted" and "spontaneous" ignitions, respectively). Given the distributions of window sizes and building heights in each tract type as well as critical fluxes for spontaneous and piloted ignition (taken here as 32.2 and 16.2 kW/m^2, respectively), we calculate the probability, as a function of separation distance, that a non-burning building's most susceptible window fuels are exposed to the necessary fluxes. Results for the baseline case are shown in Fig. 8. The increased susceptibility of moderately blast-damaged buildings has been arbitrarily simulated by tripling the flame areas associated with the windows. These probability curves are used along with the normalized building distribution [8] and the spread time probabilities (Fig. 6) in the

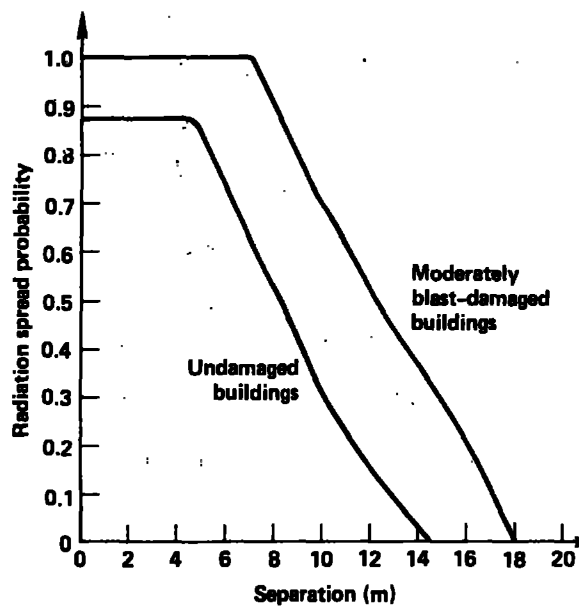

Figure 8. Simplified probabilities of fire spread by thermal radiation (with and without sparks) vs. separation of burning and unignited building.

time-dependent calculations to obtain the expected number of buildings ignited by short-range mechanisms at each time step.

Calculating the probability of spread by firebrands involves several steps. First we use empirical estimates of the number of firebrands generated per unit area of roof which are large enough (at least 6.4 cm^2 by 0.6 cm thick) to start a fire after surviving transport. Then empirical data taken at an average ambient wind speed of 1.8 m/s are scaled to the assumed ambient wind speed (2.7 m/s for the baseline case) to give a probability of a brand landing on a unit area of ground within a given brand dispersion angle as a function of range from its origin. Figure 9 shows the qualitative effects of winds for a slightly different ensemble of buildings. We next calculate the probability that the brand will land on at least one major item in a room during its descent. These calculations account for windspeed and the distribution of window sizes and major fuel locations within rooms.

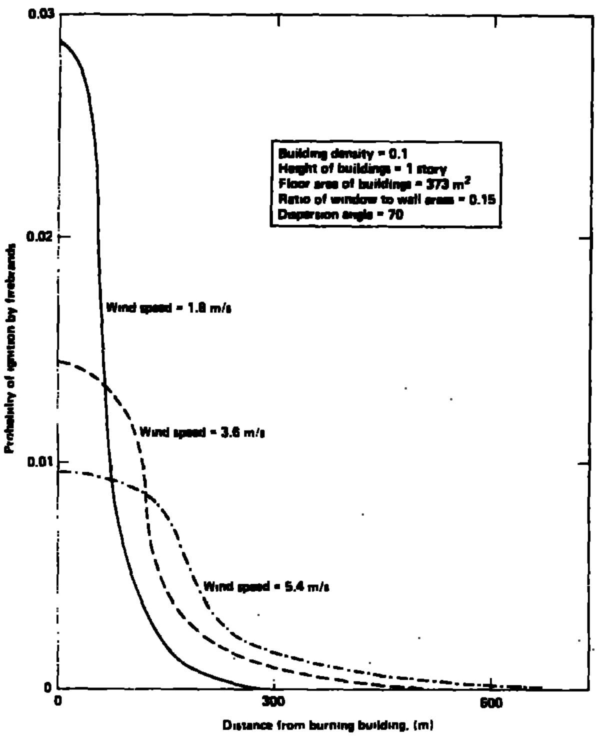

Figure 9. Probability of spread by firebrands vs. range for various ambient windspeeds. Note the small probabilities and the extent of the range, particularly for high windspeeds. (From Ref. 8)

The time-dependent spread calculations are performed as follows. First we need to describe the urban area in some way. We have chosen to break it up into a distribution of relatively homogeneous tract types. With some force-fitting, the actual urban area is represented as 0.8 x 0.8 km square tracts separated by natural or man-made firebreaks of at least 30.5 meters, which for all practical purposes is considered to be too wide for spread by short-range mechanisms. For our uniform city cases we have taken firebreaks of the minimum separation. Actual cities may have many firebreaks which are wider than this value. The various probabilities are used to calculate the expected numbers of buildings ignited by radiation or by brands in each tract at each time step. Once ignited, the buildings move through various stages of burning (using empirically-derived algorithms), until "stage 3" is reached. This is the phase during which spread to other buildings occurs, at times determined by the curves of Fig. 6. The calculations continue until the input time limit is reached, or until the number of new fires during a time step falls below some small, pre-set threshold value.

SAMPLE CALCULATIONS

We have used a numerical computer code which incorporates models of many of the physical phenomena described above. Here we present sample results for the baseline case of a uniform city. We define a "uniform city" as one composed of a single building type, of constant building density and fuel loading, infinite in extent and with constant firebreak dimensions. Parameteric studies were also performed to identify dominant parameters for a uniform city. We emphasize that these results are highly preliminary in view of the incomplete nature of the models incorporated into the code. Nevertheless, these results serve to identify problem areas which require more rigorous investigation.

Developing a computer code to calculate the smoke-generation due to fires in an urban area which incorporates all of the factors discussed above is a formidable task. Rather than develop a numerical code from scratch, we have borrowed heavily from the codes developed by Takata et al., [8,16] for the "Five-City" study of the late 1960's. While these codes do not encompass all the phenomena of present interest, it has provided an expedient computational framework from which we could delineate the major characteristics. We have added various features to the code, such as the graphics routines, and more efficient I/O. We are also currently adding variable wind direction with time. For the sake of convenience the present unified code is called the Livermore Urban Fires & Smoke (LUFS) code; details are given in [17].

Typical computation time for one case using the LUFS code was 10-15 seconds on a CRAY-1. The times are expected to increase significantly when other features are added to the program. We now discuss some of the results in greater detail.

Results: Fires in a Uniform City

Calculations were performed of the initial fire starts and their subsequent development for a uniform city. Each structure has equal combustible fuel distributions along with equal fire spread probabilities, etc. Such a study is useful as a baseline case as well as helping to identify dominant factors which strongly influence the fire and the smoke generation history.

A baseline case was chosen using currently available values for the physical processes described in Figs. 1 and 2. The baseline case has a single-burst 1 MT yield, 3 km HOB, 20 km visibility. The HOB was chosen because it maximizes the area within the overpressure contour corresponding to severe blast damage. The urban area is flat, near sea level, and composed of 2500 uniform tracts. Each tract is 0.8 x 0.8 km, with 1100 wooden, two-story buildings, and a building density of 15%. Lowest critical ignition thresholds of 7.7 and 10 cal/cm^2 were used for the window coverings and the room contents, respectively (see Fig. 4). The ambient wind had a constant velocity of 2.68 m/s (6 mph). Blast damage criteria (Fig. 3) were an overpressure of 3.5 psi for severe building damage [5], 2 psi for moderate damage, 2 psi for fire extinguishment threshold, and a uniform areal combustible fuel loading of 30 kg/m^2. Although these values are reasonable, they should be considered preliminary and subject to change depending on the urban area and attack conditions being considered.

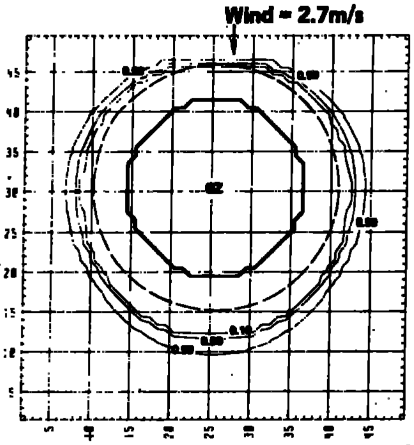

Figure 10. Contours of unburned buildings for Uniform City, baseline case. Dashed circle is 99% contour at t=0, other contours are for t=25 hr. Distance between grid lines is 4 km.

The baseline calculation results are shown in Figs. 10-11. Figure 10 shows the initially-ignited area (dashed circle) immediately following a burst above the indicated ground zero (GZ). Also shown in the figure is the severely blast-damaged area, in which the fire development is assumed to have been delayed due to the blast wave and the collapse of buildings into debris. It is possible that smoldering process may continue for some considerable time under the debris; however, this aspect is not considered in the present calculations. (Modeling the smoldering fires is currently in progress and will be incorporated into the LUFS code.) Because the extent of the ignited (and still actively burning) region is greater than that of the severely blast-damaged central area, the fires in the region of overpressure less than 3.5 psi spread to other structures within their own tracts through radiation and firebrands as well as to the nearest neighboring tracts by firebrands. Figure 10 also shows the spread at 25 hours after the burst. The numbers on the contours in the figure denote the fraction of unburned buildings in each tract. Thus the outermost contour showing .99 means that only 1% of the buildings has been consumed or is burning due to spreading fires; this can be regarded as the virtual fire front. The fires also leave behind a burned-out area, thus creating an annular fire "ring" around the GZ. This is what one would expect from actual mass conflagrations and from field tests, such as those conducted in Japan [18]. The wind velocity was taken to be constant at 2.68 m/s (6 mph) in the downward direction. The effect of this wind on the fire history can be seen in the non-concentric nature of the fire-ring at 25 hr, i.e., the fire has spread farther in the downwind direction than in the crosswind direction. As presently constituted, the fire spread due to firebrand transport is only possible within a specified dispersion angle about the wind direction. The fire spread due to radiation proceeds in all directions, so long as the view factor is not zero. However, spread from one tract to another is only possible by brands.

The magnitude of the urban area affected by the explosion is shown in Fig. 17 below. It shows that the area either destroyed by blast or initially-ignited is 513 km^2. Of this, 226 km^2 is in the severely blast-damaged region; most of the rest is in the moderately blast-damaged region. During the course of burning for the next 25 hours the damaged area almost doubles, to 980 km^2. The cumulative fuel consumed in urban fires is expected to be of major importance for modeling the smoke generation history. The rate of fuel consumption may also be important in predicting the smoke properties, and possibly for predicting the development of firestorms. Figure 11 shows the rate of fuel consumption for the entire urban area, from which we observe that the intensity of fires peaks about 5 hours after the burst and subsides to a moderate level thereafter. The cumulative fuel consumed is the time integral of this curve; see Fig. 18 below for the baseline case. (The factors given in parentheses of the titles for the rate of fuel consumption and the cumulative fuel consumption allow conversion of the ordinates to energy or power if one assumes wood-equivalent heat release, i.e., 18.6 MJ/kg of fuel.) As noted above, we have taken the amount of the fuel available for active combustion to be one-half of the fuel in the structure. The figure shows that fuel consumption accelerates in the early stages during which both the initially-ignited and the newly-ignited areas are burning, and settles down to a quasi-steady level at later stages, reflecting the fact that at this point new areas are becoming involved in fires at a constant rate.

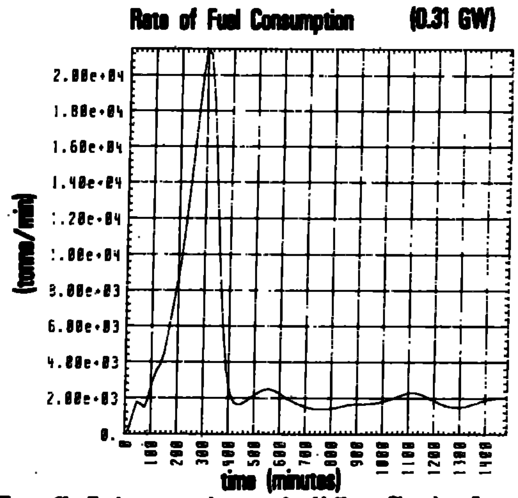

Figure 11. Fuel consumption rate for Uniform City, baseline case.

Figure 18 also gives some indication of the amount of smoke produced. For the baseline case, the fires are seen to have consumed approximately 5.4 Tg of fuel in 25 hours. Assuming the smoke generation of wood to be about 1% of the mass consumed [13,14], about $5.4 \cdot 10^7$ kg of smoke particles would be released into the atmosphere from such an urban fire in 25 hours. Although this magnitude appears to be reasonable, much more fundamental analysis (both modeling and experiments) must be done to produce a more credible number.

Now that we have the basic characteristics of the urban fire history for the baseline case, we proceed to the parametric study to identify the dominant factors which influence the fuel consumption.

Many input parameters are required for the present calculations using the LUFS code. All of these factors have been examined for their relative impact on the outcome of fires and the fuel consumption processes. Here we discuss only some of the more dominant parameters. These are: wind, atmospheric visibility, firebrand generation rate, specific fuel loading, ignition thresholds, and secondary ignitions. More details can be found in Ref. 17.

Wind

Calculations were performed by varying the magnitude of the wind by a factor of two and three, viz., W = 5.4 m/s (12 mph), and W = 8.0 m/s (18 mph). The more extreme case of an 8.0 m/s wind is shown in Fig. 12. Compared to the baseline case of W = 2.7 m/s, the fires have now spread much farther after 25 hours. The shape of the fire ring is now more eccentric. The cumulative fuel consumption for these different wind velocities is shown in Fig. 13. It can be seen that the effect of increased wind is to increase the slope of the curve, especially at the later stages of fire, resulting in a much greater fuel consumption. We must point out that it is rather unrealistic to assume a wind of such magnitude (8 m/s) sustained for a long period of time in the same direction. However, these calculations suggest the very plausible conclusion that wind has a dominant effect on fire history in a uniform city. This is particularly reasonable when one recalls that the accelerated burning of buildings due to increased wind and the interactive effects of wind on fire spread have thus far been neglected.

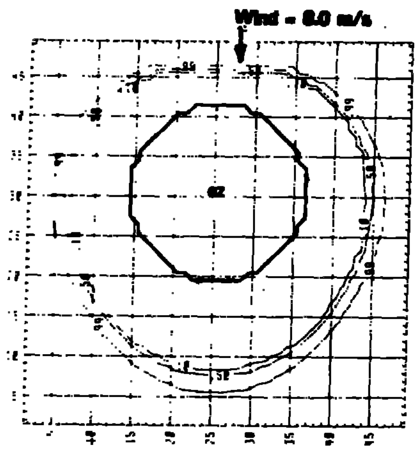

Figure 12. Contours of unburned buildings for Uniform City, wind = 8.0 m/s, t=25 hr. Distance between grid lines is 4 km.

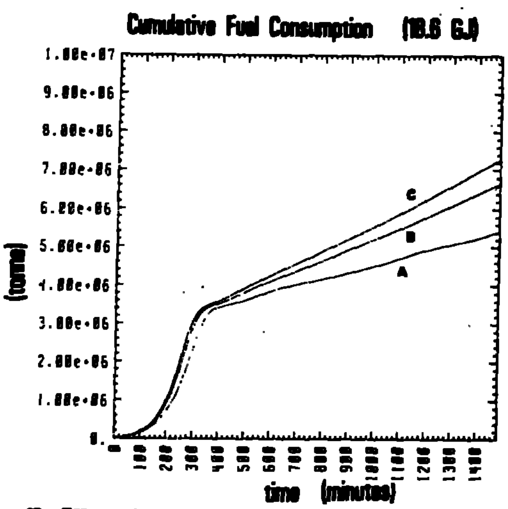

Figure 13. Effect of wind on cumulative fuel consumption, Uniform City. (A = 2.7 m/s (baseline), B = 5.4 m/s, C = 8.0 m/s)

Visibility

In the baseline case a visibility of 20 km was used, representing a reasonably clear day. The visibility was changed to 12 km (a cloudy day), and 32 km (a very clear day). A greater visibility enhances the fuel consumption enormously. On the other hand, lowering the visibility seems to affect the fuel consumption only in the early stages. For although reducing the visibility greatly reduces the thermal fluence reaching points away from GZ, the secondary ignitions are not affected. It happens that for our baseline case, the "reach" of the thermal ignitions is only slightly beyond the 2 psi overpressure contour, which marks the limit of the secondary ignitions. Hence reducing the visibility in this case reduces the number of initially-ignited buildings, but not the area initially involved in fire. For the uniform city this delays but does not greatly change the subsequent fire development. For a different attack scenario this need not be true, so visibility can play a strong role in the fuel consumption history, and consequently the smoke production.

Firebrand Production

In the baseline case an empirically-obtained value of 15 pieces of firebrands/m^2 of collapsing roof area was used [16]. When this parameter value was varied to one-half and two times the baseline case, the fuel consumption history is considerably affected (Fig. 14). Therfore, this parameter is clearly one of the dominant factors. Tests of different roofs are needed to put our understanding of the firebrand production characteristics on a sounder basis, however.

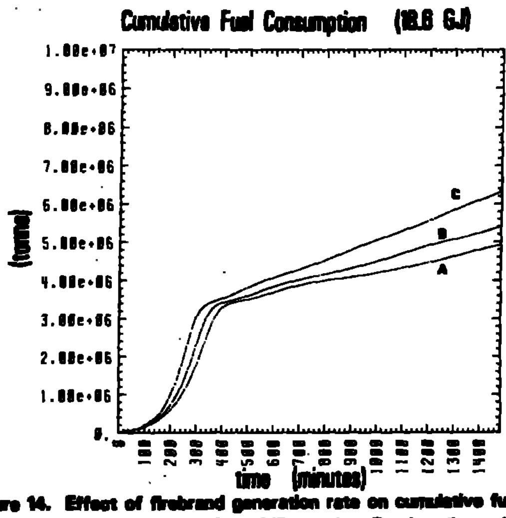

Figure 14. Effect of firebrand generation rate on cumulative fuel consumption, Uniform City. (A = 1/2 baseline, B = baseline value, 15 per m**2 of roof, C = twice baseline).

Fuel Loading

Calculations were made for the cases of 200 and 50 kg/m^2-floor, representing twice and one-half of the baseline value for the specific fuel loading (Fig. 15). Thus the amount of fuel loading distributed in an urban area greatly affects the amount of fuel consumed, suggesting that a thorough survey may be necessary for a given urban area. The crossover of the curve for the 200 kg/m^2 case is due to the tremendous amount of fuel per burning building and the consequent longer building time.

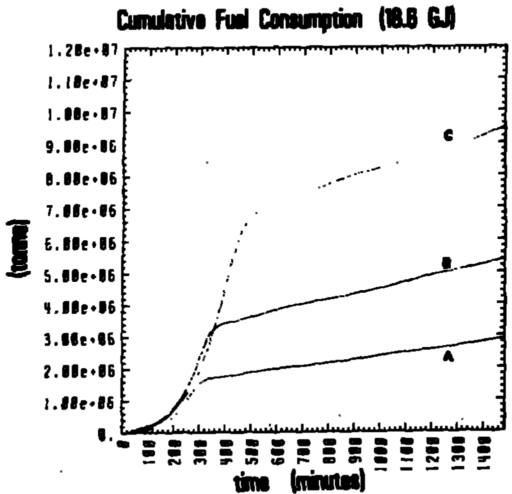

Figure 15. Effect of specific fuel loading on cumulative fuel consumption, Uniform City. (A = 50 kg/m**2-floor, B = 100 (baseline), C = 200).

The areal fuel loading (fuel loading per total area of ground) for these three cases is 60, 30, and 15 kg/m^2, respectively. These are all for the baseline building density of 15%. Similar areal fuel loadings can be obtained by varying both the specific fuel loading and building density. However the results are not simply a function of areal fuel loading since the building burntimes depend on the specific fuel loading and the spread characteristics depend on the building density.

Ignition Threshold

The lowest of the four critical ignition values for window coverings was lowered to 5 and raised to 10 cal/cm^2 from the baseline value of 7.7. Reducing the ignition threshold greatly increases the total fuel consumption, whereas increasing the threshold appears to cause only a minor perturbation to the baseline results. The lower value of 5 cal/cm^2 is considered to be the lowest possible value for the materials being used in urban dwellings. The reason for the dominant effect on the fires at this ignition threshold value is that the initially ignited area from the fireball is much larger than that for the baseline case, thus helping the fires to continue at a very robust rate even many hours after the initial burst.

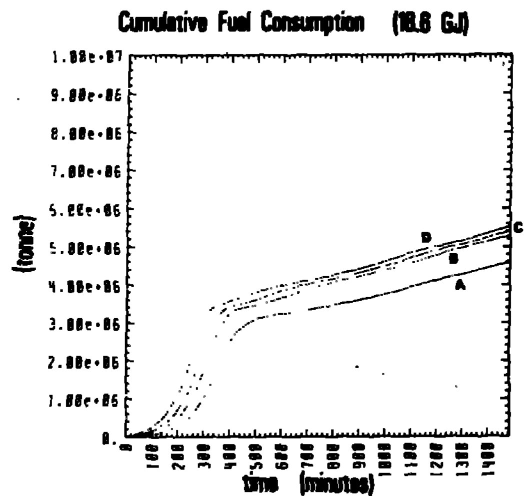

Figure 16. Effect of secondary ignitions on cumulative fuel consumption, Uniform City. (A = no secondary ignitions, B = 1/2 baseline, C = baseline (1 fire per 10,000 m**2 of floor), D = twice baseline).

Secondary Ignition

Secondary ignition refers to the fires started as a consequence of blast wave passage through the target area. Three cases were calculated: the frequency of secondary ignitions increased by a factor of two, decreased by a factor of two, and set to zero (Fig. 16). The changes in the total fuel consumption are relatively small for non-zero values; however, it shows sizable reduction in fuel consumption for the zero case. This is a consequence of the fact that for our baseline case the secondary ignitions happened to be particularly important near the outer edge of the initially-ignited region. We must also bear in mind that the data base upon which the frequency of secondary ignitions is estimated is very limited. At this point we can only conclude that secondary ignitions deserve continued attention.

DISCUSSION

There are other important problem areas that have not been addressed in the present preliminary analysis. We shall discuss only two of these here: the firestorm and the fire merging/breakup processes. From the standpoint of global smoke transport phenomena, firestorms represent a potentially important mechanism which may lift the particles to high altitudes from which these particles might spread laterally on a meso or global scale, thus affecting the solar radiation absorption and scattering processes. Disagreement exists among experts on the correct onset criteria of the firestorm (see, for example, Refs. 19 and 20). On two major points, however, there is agreement: the fire intensity and the extent of the fires must be quite large, typically on the order of 250 KW/m^2 encompassing an area of tens of square kilometers. The frequency of firestorms during post-nuclear urban fires is believed to be small; however, because of their considerable potential impact on smoke transport they cannot be ignored. In the many calculations performed during the parametric studies none of the cases satisfied both of the above criteria for initiation of a firestorm. Since firestorms are inherently three-dimensional in nature, and probably develop by means of interaction between the fire-incuded winds and the fires, much more work is necessary to determine their frequency.

Another area of concern is the fire merging and breakup phenomena, in which we also include fire whirl. The sizes and shapes of these fires are important in characterizing the fire-plume interactions and the subsequent smoke-particle rise in the plume. At present there does not seem to be any analysis available of the breakup and/or merging characteristics of urban fires. Therefore this represents another potentially fruitful area of research.

Although we have been discussing only the case of a uniform city, the present code can calculate the fire history in a representation of a real city, one in which building types and fuel loading distributions are non-uniform. Calculations were performed for the San Jose urban area, circa 1968, with a 1 MT burst at 2.4 km altitude over the city. Details of the results are given in Ref. 17. Here we show only two results. Figure 17 shows the area burn history as a funtion of time for the 25 hour period after the burst over the southern tip of San Francisco Bay. The area affected by fires is approximately 200 km^2. Also shown in the figure is the magnitude of the burn area for a uniform city. Note the considerable difference in the two values. This suggests that the fire history is "city-specific", meaning that the distribution patterns of a particular city will make a

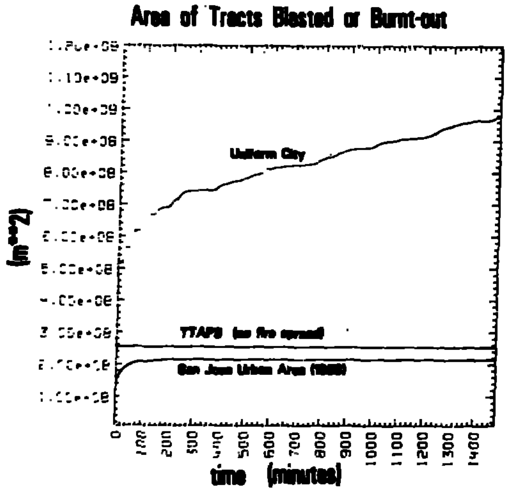

Figure 17. Area affected by blast or fire: Uniform City (baseline case), San Jose urban area (1968), TTAPS estimate (Ref. 3).

great difference in the outcome of the fire history. The estimated burn area of the TTAPS study [3] is also plotted in the figure for comparison. Their value was obtained for what might be called a composite uniform city, i.e., a uniform, high-rise downtown portion occupying 5% of the total area and the rest occupied by a uniform suburban area. The cumulative fuel consumption is shown in Fig. 18 for the same cases.

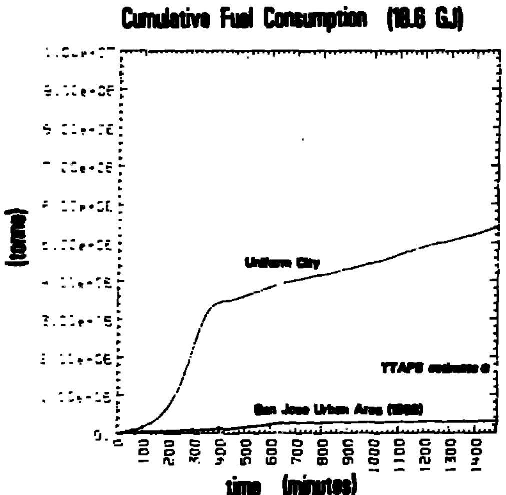

Figure 18. Cumulative fuel consumption: Uniform City (baseline case), San Jose urban area (1968), TTAPS estimate (Ref. 3).

Again, we observe a much lower value for the San Jose (1968) case than either the TTAPS or the uniform city case. This is partly due to the lower average areal fuel loading, lower average building density, and its non-uniform character, which reduce the rate of fire spread and the extent to which an ignited tract burns out. We therefore reiterate that a comprehensive survey of the combustible fuel distributions is a necessary condition for predicting the fire-development history for any realistic urban area.

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